Flight Acceptance Testing of the Two JPL Planck Sorption Coolers

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ABSTRACT

The Jet Propulsion Laboratory has built and delivered two continuous closed-cycle hydrogen Joule-Thomson (J-T) cryocoolers for the European Space Agency (ESA) Planck mission, which will measure the anisotropy in the cosmic microwave background. The sorption cooler provides cooling in two different locations: it directly cools the Planck Low Frequency Instrument (LFI) below 22.5K while providing a precooling stage for a 4 K J-T cooler for the High Frequency Instrument (HFI). The temperature stability at the LFI interface is required to be less than 100 mK; while that of the HFI must be below 450 mK. The two coolers have been designed to provide 650 mW and 200 mW for the LFI and HFI, respectively, with a total input power of 470 W, excluding electronics. The performance of these coolers is mainly a function of the compressor interface and final precooling stage temperatures. We present results from the testing of these two coolers for the input power, cooling power, temperature, and temperature fluctuations over the flight allowable ranges for these interfaces.

INTRODUCTION

Planck is a European Space Agency (ESA) mission that will launch in late 2007 to measure the Cosmic Microwave Background (CMB). Two instruments, the High Frequency Instrument (HFI) and the Low Frequency Instrument (LFI) will measure the CMB from 30 to 957 GHz. The Planck hydrogen sorption cryocooler will directly cool the LFI while providing precooling for the HFI cooler chain.[1] The sorption cooler consists of a six-element sorption compressor and a Joule-Thomson (J-T) cryostat.[2] The cooler produces liquid hydrogen in two liquid-vapor heat-exchangers (LVHX) whose temperatures are stabilized by hydrogen absorption into three compressor elements. LVHX1 provides cooling for the HFI instrument, while LVHX2 cools the LFI instrument. The vapor pressure of the liquid hydrogen in the LVHXs is determined primarily by the absorption isotherms of the hydride material used in the compressor elements. Thus, the heat rejection temperature of the compressor elements determines the instrument temperatures. On the spacecraft the compressor rejects heat to a heat-pipe radiator with flight allowable temperatures between 262 and 282 K.

As with many space cryogenic missions, the Planck sorption cooler depends on passive cooling by radiation to space. This is accomplished on Planck by three V-groove radiators.[1] The final V-groove is

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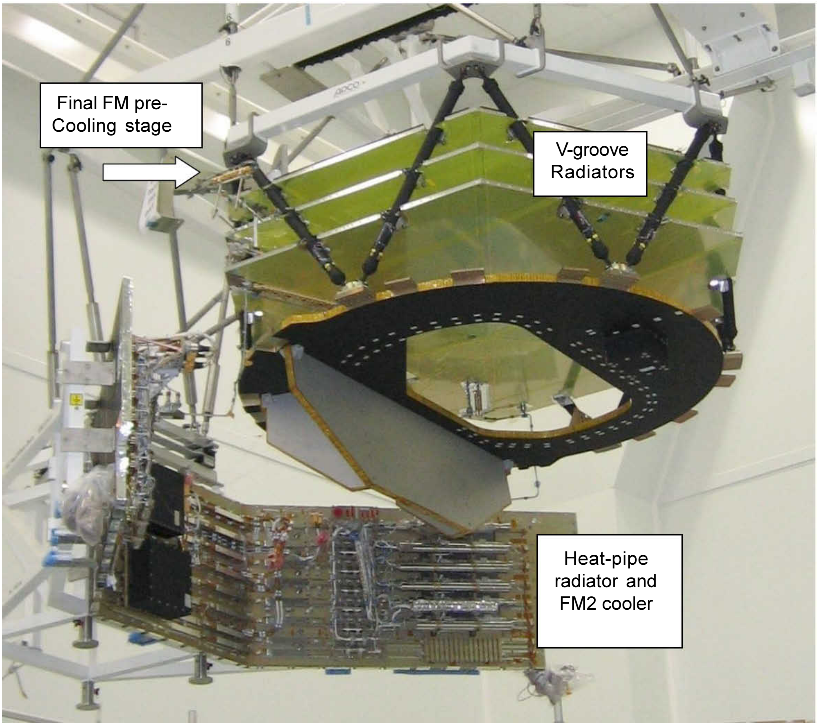

Figure 1. Planck Sorption Coolers integrated to the spacecraft interfaces.

required to be between 45 and 60 K to provide the required cooling power for the two instruments. At 60 K, with a working pressure of 4.8 MPa, the two sorption coolers produce the 990 mW of required cooling power for the two instruments. Figure 1 shows the two sorption coolers integrated to the spacecraft radiator and the flight V-grooves.

SORPTION COOLER DESCRIPTION AND OPERATION

To provide complete redundancy for the mission, two sorption coolers were built and delivered. Flight model one (FM1) was delivered to ESA in May 2005, and flight model two (FM2) was delivered in August 2005. The two coolers are functionally identical. Each consists of a sorption compressor (SCC) and a piping assembly and cold end (PACE). The as-built compressors are identical, while the two as-built PACEs are mirror images of each other with some minor differences in the lower piping sections. Figure 2 shows the FM1 configuration. A French team is building the flight electronics. Due to schedule conflicts, Jet Propulsion Laboratory (JPL) built its own non- flight electronics for the testing discussed in this paper. Testing was performed with flight-like qualification models of the flight electronics, but will not be discussed here. Due to the commonality of the two coolers, the following description applies to both coolers.

The sorption cooler compressor consists of six compressor elements, high-pressure stabilization tanks (HPST), and the low-pressure stabilization bed (LPSB). The compressor elements and the LPSB use $La_{1.0}Ni_{4.78}Sn_{0.22}$ as the hydride material. Each compressor element includes a hydride actuated gas-gap heat switch that thermally couples or isolates the compressor element from the warm radiator interface. Gas compression is realized by heating a compressor element to ~200 °C. At any time, one element is heating, one element is providing gas at the operational pressure, one element is cooling down, while three elements are absorbing gas. The HPST consists of 4 one-liter tanks and serves to stabilize the high-pressure manifold. The LPSB, in addition to damping pressure oscillations in the low-pressure manifold, is used to store hydrogen gas so that the cooler can be shipped at a pressure below atmospheric pressure. The two manifolds are separated from the compressor elements by check valves that control flow into and out of the compressor elements.

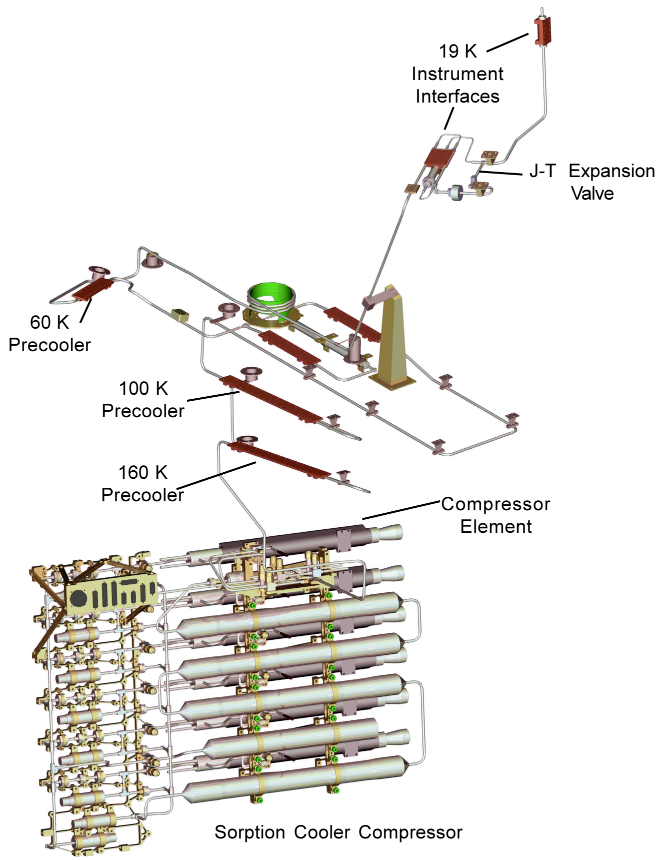

Figure 2. Model of the FM1 sorption cooler. FM2 sorption compressor is identical, while the piping sections (PACE) is a mirror image. The PACE precoolers attach to the spacecraft V-grooves. The sorption compressor attaches to the warm radiator panel.

The PACE consists of a tube-in-tube heat exchanger, three pre-cooler stages, a porous plug J-T expander, and two liquid-vapor heat exchangers (LVHXs). The three precooling stages, PC1, PC2, and PC3, attach to the three V-grooves, and are nominally at 160, 100, and 52 K. respectively. PC3 consists of three interfaces to the V-groove, PC3A, PC3B, and PC3C to distribute the heat removed from the gas stream to different locations on the 3rd V-groove. The temperature of the last pre-cooler, PC3C, determines the cooling power. Between the PC3C and the J-T, a high efficiency heat-exchanger precools the gas stream. After the J-T, the two-phase mixture passes through the 2 LVHXs. LVHX1, is required to remove 190 mW while LVHX2 removes 646 mW. The vapor pressure, and hence the temperature of the LVHXs, is established by the three absorption compressor elements.

A temperature stabilization assembly (TSA), using PID control, is placed between LVHX2 and the instrument interface to reduce temperature fluctuations. The TSA consists of two thermal resistors on each side of the control stage. 150 mW for temperature control power is allocated. This is in addition to the 836 mW required for the instruments, for a total of 986 mW.

For a final precooling temperature of 60 K, the J-T expander is selected so that the required mass flow is produced with an inlet pressure of 4.8 MPa. The end-of-life input power, excluding electronics, is 470 W (BOL is 426 W). These design choices result in a compressor cycle-time of 667 seconds for a 60 K pre-cooler.[2] For lower pre-cooler temperatures the cooling power increases and the system is operated at a lower pressure to produce about 50 mW of excess cooling. This results in lower input power and a

Table 1. Planck Sorption Cooler Requirements

LVHX1 Temperature	< 19 K
LVHX2 Temperature	< 22.5 K
LVHX1 Temperature Fluctuations	< 450 mK
LVHX2 Temperature Fluctuations	< 100 mK
Cooling Power	> 986 mW (646 mW for LFI, 190 mW HFI, 150 mW for TSA
Input Power (excluding electronics)	<426 W (BOL)

Interface Flight Allowables

Warm Radiator	262-282 K
Final pre-cooling stage	45-65 K

longer cycle-time. The Planck sorption cooler requirements are summarized in Table 1 with the flight allowables for the two critical interfaces.

TEST FACILITY

The test facility has been described in detail elsewhere.[3] Briefly, it is a vertical test chamber in which both the SCC and PACE are mounted to thermal interfaces that simulate the warm radiator and final precooling stage. Due to size constraints the two subsystems could not be placed in the flight configuration. A temporary piping umbilical that joins the two does not impact the performance. A schematic of the test facility is shown in Figure 3.

The SCC is mounted to a set of 6 thermally isolated chiller plates that provide the interface temperature conditions and removes the heat from the compressor. A BOC Edwards chiller circulates the refrigerant through common manifolds to each plate. Each plate is instrumented with a thermometer. The rest of the compressor interface points attach to a large plate that is cooled by the same chiller. The entire com-

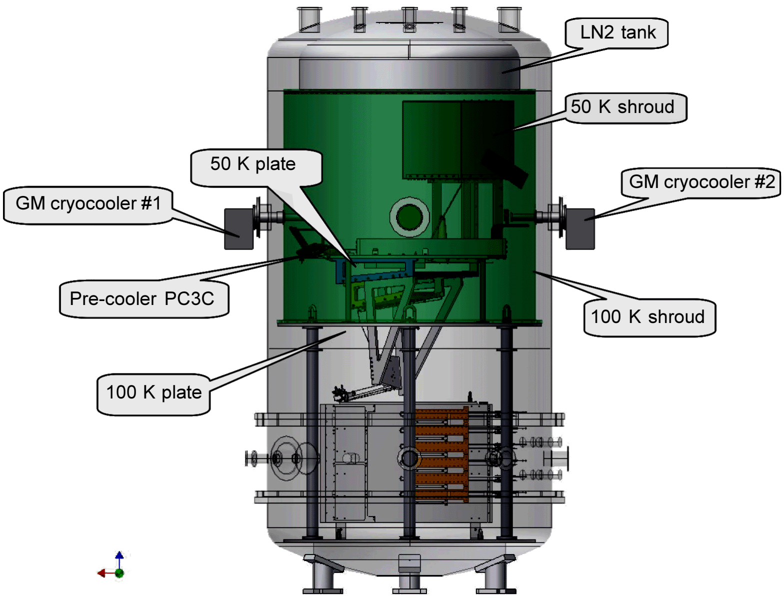

Figure 3. Test facility for Planck sorption coolers. Cryogenic portions of the cooler are surrounded by 100 K shroud, which is cooled by liquid nitrogen tank. 50 K portions are cooled by two GM coolers. Instrument interfaces are contained within the 50 K shroud. Compressor interface is thermally controlled by a chiller over the flight allowable range.

pressor is covered with MLI. The PACE, on its support fixture, is mounted into the chamber on 4 thermally isolating posts. The final precooling stage, PC3C, and all components below it are thermally isolated from the support structure to reduce the parasitics below 50 mW, so that the cooling power can be measured to this level. The PACE support structure is cooled using the first stages of two (CTI Model 1020 Cryodyne) Gifford-McMahon (G-M) coolers. This structure and the cooler components thermally attached to it, PC3 A&B, PC2, and PC1, typically ran between 40-50 K during the testing. The only impact on performance was from PC3 A&B being at a lower temperature than PC3C, which increased the cooling capacity slightly. The second stage of one of the GM coolers cools a shroud that covers the cold end to about 20 K, so as to reduce the radiative parasitics to a negligible level. The temperature of the shroud is controlled with a heater/thermometer using PID control. The 2^{nd} stage of the other cooler controls, along with another PID system, the temperature of the PC3C interface to the flight allowable. A copper block with a heater and thermometer are attached to each LVHX. This allows simulated instrument loads to be applied and to measure the cooling power. A large MLI covered shroud, cooled by a liquid nitrogen tank to about 90 K, enclosed the entire cold end. MLI was used to cover the PACE and its structure. A turbo-pump system, along with the GM coolers reduced the pressure in the chamber to 10^{-7} Torr.

LabView software was used to control the two interfaces and to supply power for the cooling power measurement. In addition, the facility was instrumented with thermometry to characterize the facility. All of the testing reported here was performed with ground support electronics. The electronics was controlled using LabView software and was designed to simulate all sorption cooler operations.

RESULTS

Testing results for both coolers are presented in Tables 2 and 3. The results are presented as a function of the warm radiator and PC3C temperatures. Each of the four main requirements will now be discussed. For FM1 five interface conditions were tested, while for FM2 four were tested, as the minimum power, 282/60 K, was not tested. Total test time for each cooler was greater than 1000 hours.

Temperature

The maximum instrument interface temperatures occur at the maximum value for the two interfaces: 282 K for the warm radiator and 60 K for the final precooling stage. For the FM1 and FM2, LVHX1 was 18.63 K and 18.4 K respectively. Both coolers satisfy the requirement of < 19.0 K.

For LVHX2 interface the temperatures at these interface conditions are 20.73 and 18.4 K, for FM1 and FM2 respectively. These temperatures are measured at the TSA stage for LVHX2. The large difference between the two is attributable to the different design of the TSA stage. During the FM1 testing the

Table 2. Flight Model One Test Results

	Max Temperature	Max Power	Min Temperature	Min Power	Nominal	Req'd
$T_{radiator}/T_{PC3c}$ (K)	282/60	262/60	262/45	282/45	272/52	
LVHX1 T (K)	18.63	17.12	16.71	17.97	17.1	< 19.02
LVHX2 T (K)	20.73	18.6	18.4	19.4	18.7	< 22.5
LVHX1 ΔT (mK)	442	485	457	433	400	< 450
LVHX2 ΔT (mK)	159	100	156	93	116	< 100
TSA Power (mW)	149	146	280	164	85	< 150
Cooling Power (mW)[1]	1116	1100	1050	1085	1070	□990
Input Power (W)[2]	387.2	408.1	297.4	277.0	345.2	< 426

Table 3. Flight Model Two Test Results

	MaxTemperature	Max Power	Min Temperature	Min Power	Nominal	Req'd
$T_{radiator}/T_{PC3c}$ (K)	282/60	262/60	262/45	282/45	272/52	
LVHX1 T (K)	18.4	17.22	16.53	N/A	17.15	< 19.02
LVHX2 T (K)	19.7	18.6	18.05	N/A	18.7	< 22.5
LVHX1 ΔT (mK)	374	427	400	N/A	374	< 450
LVHX2 ΔT (mK)	91	97	112	N/A	147	< 100
TSA Power (mW)	91	88	113	N/A	167	< 150
Cooling Power (mW)[1]	1116	1100	1050	N/A	1060	□990
Input Power (W)[2]	386.8	407	304.1	N/A	345.2	< 426

design was changed in order to lower the observed anomalous temperature fluctuations (see next section). The new design results in a lower temperature, so retesting the FM1 at these interface conditions was not considered necessary. For all other interface conditions, the temperature requirements are met, as expected.

Temperature Fluctuations

From Tables 2 and 3, the temperature fluctuation requirement is not met for both FM1 and FM2 coolers for some of the interface conditions. For the FM1 cooler, the requirement is exceeded both for LVHX1 and LVHX2 interfaces, while for FM2 only the LVHX2 requirement is exceeded. In addition, for

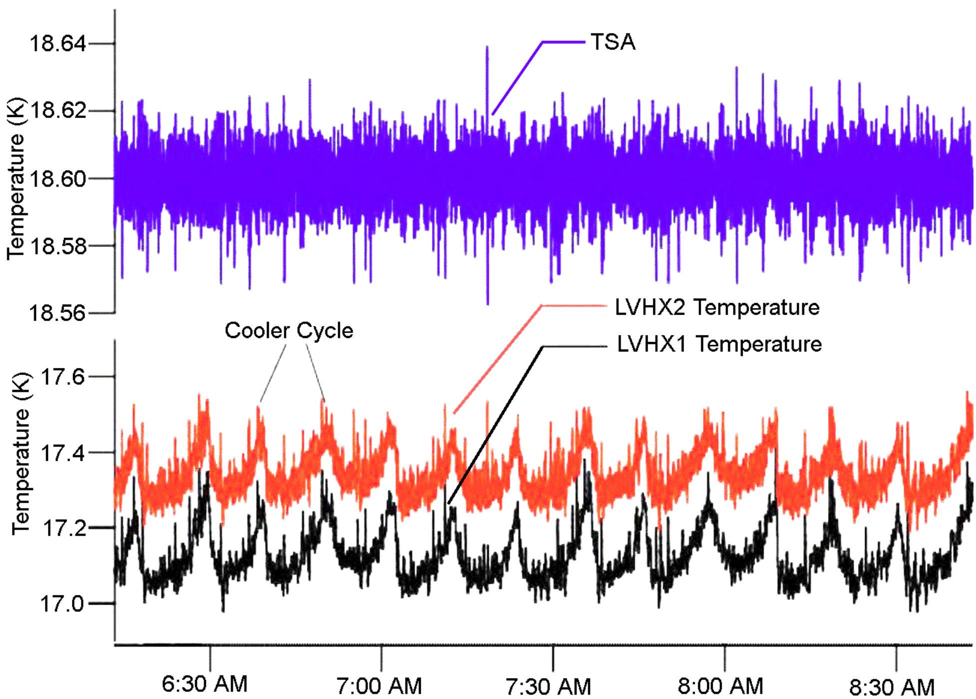

Figure 4. Typical cold-end fluctuations. TSA stage is PID controlled.

both coolers the TSA allocation is sometimes exceeded. This is only of consequence if the total cooling power requirement cannot be met. This was never the case. Temperature fluctuations in the sorption cooler are due primarily to a low frequency contribution at the compressor element cycle time and higher frequency contributions due to two-phase flow phenomena in the cold end. Figure 4 shows typical temperature fluctuations where both types of fluctuations can be seen. Note the different scale for the PID controlled TSA fluctuations compared to the two LVHXs.

In testing a previous engineering model sorption cooler, the fluctuation requirements were met for all interface conditions. An investigation into the higher levels concluded that the cause was due to orientation differences of the cold-ends in the two systems; this led to an increase of the two-phase flow contribution. During the engineering testing campaign the LVHX2 body was horizontal, while during the flight testing it was held at a 12.5 degree angle. This orientation led to pooling of liquid that in turn caused flow irregularities and two-phase plug flow events. The increase in temperature fluctuations is caused by a temporary increase in the cold pressure due to sporadic evaporation of liquid plugs. It is believed that in a microgravity environment, flow irregularities due to gravity pooling will be absent and the temperature fluctuation requirement will be met. A waiver to the requirements was given based on this analysis.

Cooling Power

As shown in results in Tables 2 and 3, the cooling power requirement of 990 mW is satisfied for both coolers and for all interface conditions. The minimum available cooling power is for a 60 K final precooling stage, although all measured values are approximately the same. This is because for lower pre-cooler temperatures the cooler is operated at a pressure to produce an excess of approximately 50 mW above the requirement. This is done to increase the sorption compressor lifetime and to reduce the input power.

As discussed above, the TSA allocation is exceeded for some cases, but this is not an issue as long as the total available cooling is greater than 986 mW. Exceeding the TSA allocation is related to the temperature fluctuation problem discussed above. The random nature of the plug flow events makes it difficult to control the system. In order to deal with the higher fluctuation levels, the power applied to the TSA needs to be increased. If as expected, the fluctuation levels decrease, then the TSA power will also decrease.

An additional complication to the cooling power results is that PC3 A&B were not controlled and were typically at 40 K. This leads to the gas stream leaving PC3C being at a lower temperature than the pre-cooler temperature, which leads to an enhanced cooling power. Modeling of this effect was performed and the excess was 50 mW. The results in the two tables have been corrected for this effect.

Input Power

The majority of the input power consists of the heatup power and the desorption power. The heatup power is the amount of power needed to heat a compressor element to the desorption pressure. This will be a maximum for the 262 K warm radiator temperature. The desorption power is the heat needed to maintain the compressor element at the desorption pressure to produce the required mass flow. As was discussed above, as the final pre-cooler temperature decreases, the available cooling power increases and less mass flow is required. Thus the maximum desorption power is for a 60 K final pre-cooler. The beginning of life power requirement is 426 W. From Tables 2 and 3, the beginning-of-life power was 408 W for the 262 K warm radiator and 60 K pre-cooler case. Input powers for all other cases are lower.

CONCLUSIONS AND CURRENT STATUS

Flight acceptance testing of the two JPL sorption coolers has been performed. The coolers met all requirements except for temperature fluctuations. The higher level of temperature fluctuations is due to gravity pooling leading to two-phase plug flow events. A waiver was granted based on the fact that gravity pooling will be absent in micro-gravity.

The two coolers have been delivered to ESA and have just recently undergone spacecraft-level testing, with the results being similar to the JPL results.

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